

On a Weyl–von Neumann type theorem for antilinear self-adjoint operators

by

SANTTU RUOTSALAINEN (Helsinki)

Abstract. Antilinear operators on a complex Hilbert space arise in various contexts in mathematical physics. In this paper, an analogue of the Weyl–von Neumann theorem for antilinear self-adjoint operators is proved, i.e. that an antilinear self-adjoint operator is the sum of a diagonalizable operator and of a compact operator with arbitrarily small Schatten p -norm. On the way, we discuss conjugations and their properties. A spectral integral representation for antilinear self-adjoint operators is constructed.

1. Introduction. This paper is concerned with an analogue of the Weyl–von Neumann theorem for self-adjoint antilinear operators on a complex Hilbert space \mathcal{H} . The Weyl–von Neumann–Berg theorem states that a complex linear normal operator is the sum of a diagonalizable operator and an arbitrarily small compact operator. An operator is diagonalizable if it has an orthonormal set of eigenvectors spanning \mathcal{H} . Motivated by the occurrence of antilinear operators in a wide range of mathematical physics applications, it is natural to inquire whether there is a Weyl–von Neumann type theorem for antilinear operators. We will show that any antilinear self-adjoint operator is the sum of a diagonalizable operator and an operator of arbitrarily small Schatten p -norm.

The Weyl–von Neumann theorem and its ramifications have been near the center of operator theory for the majority of the past century and have led to new operator-theoretical techniques. In 1909 Weyl proved that a self-adjoint complex linear operator can be diagonalized modulo an arbitrarily small compact operator [27]. In 1935, von Neumann extended this result to unbounded operators and showed that the compact operator can be taken to be Hilbert–Schmidt [24]. Halmos [13] raised the question if there exists an analogous result for normal operators. Berg [4] and Halmos himself [14], with a different technique, proved that any normal operator is diagonalizable

2010 *Mathematics Subject Classification*: Primary 47A55; Secondary 47B10, 47B15.

Key words and phrases: antilinear operator, diagonalizable operator, Weyl–von Neumann theorem, conjugation.

modulo a compact operator. Voiculescu's result is the most general one stating that also for normal operators the compact perturbation has an arbitrarily small Hilbert–Schmidt norm [26].

For complex linear operators on finite-dimensional spaces, unitary diagonalizability is one of the many conditions equivalent to normality [12, 7]. For antilinear operators, and for real linear operators in general, these conditions are no longer equivalent and the notion of normality is not so straightforward. Antilinear self-adjoint operators on finite-dimensional spaces can be unitarily diagonalized, whereas an antilinear operator commuting with its adjoint may not admit such a diagonalization in general. This is how self-adjointness of antilinear operators is an analogue of normality of complex linear operators. Therefore, it is a natural question to ask what is the analogue of the Weyl–von Neumann theorem in the antilinear infinite-dimensional setting. In addition, as the spectral theory of real linear operators in general is not totally understood, a Weyl–von Neumann type theorem would be informative about spectral properties of antilinear self-adjoint operators.

Antilinear operators appear in a plethora of applications and their usefulness has not remained unnoticed [16, 6, 20]. Antilinear operators are found in the study of planar elasticity in the form of the Friedrichs operator [25]. In inverse problems they arise in solving the so-called ∂ -bar equation in the plane [3]. In quantum mechanics antilinearity is classically noted in studying time reversal but antilinear operators are useful in the Hartree–Bogolyubov theory in nuclear physics [16], in studying quantum entanglement [1] and quantum teleportation [23]. In addition, self-adjoint antilinear operators are naturally linked to complex symmetric operators which are of importance in mathematical physics [8, 9, 10].

The paper is organized as follows. In Section 2, notation, basic notions and properties of real linear and antilinear operators are given. Conjugations and their diagonalizability are studied and antilinear projections onto a closed subspace are discussed. In Section 3, the representation of an antilinear self-adjoint operator as a spectral integral is developed. In Section 4, the main theorem, Weyl–von Neumann type theorem for antilinear self-adjoint operators, is proved. The connection to complex symmetric operators is presented.

2. Antilinear operators and conjugations. Let \mathcal{H} be a separable Hilbert space over \mathbb{C} . An operator A on \mathcal{H} is said to be *real linear* if it is additive and commutes with multiplication by real numbers. It is called *complex linear* if in addition it satisfies $Ai = iA$, and *antilinear* if $Ai = -iA$. The set of real linear operators is a real Banach algebra with the operator norm

$$\|A\| = \sup\{\|Ax\| : \|x\| = 1\}$$

and it is denoted by $\mathcal{B}(\mathcal{H})$. Every real linear operator A can be decomposed as

$$(2.1) \quad A = A_0 + A_1$$

with $A_0 = \frac{1}{2}(A - iAi)$ complex linear and $A_1 = \frac{1}{2}(A + iAi)$ antilinear.

A number $\lambda \in \mathbb{C}$ is in the *spectrum* $\sigma(A)$ of A if $A - \lambda$ is not invertible in $\mathcal{B}(\mathcal{H})$. The number λ is an *eigenvalue* and is in the *point spectrum* $\sigma_p(A)$ if there exists a non-zero vector $x \in \mathcal{H}$ such that $(A - \lambda)x = 0$. The number λ is in the *approximate point spectrum* $\sigma_a(A)$ if there is a sequence of unit vectors $\{x_n\}_{n \geq 1} \subset \mathcal{H}$ such that $(A - \lambda)x_n \xrightarrow{n \rightarrow \infty} 0$ in \mathcal{H} . The number λ is in the *compression spectrum* $\sigma_c(A)$ if the range $\mathcal{R}(A - \lambda)$ is not dense in \mathcal{H} .

The *adjoint* A^* of a real linear operator A is defined by

$$\operatorname{Re}(Ax, y) = \operatorname{Re}(x, A^*y) \quad \text{for all } x, y \in \mathcal{H},$$

where (\cdot, \cdot) is the inner product in \mathcal{H} . Equivalently, using the representation (2.1), we can define

$$A^* = A_0^* + A_1^*,$$

where A_0^* and A_1^* satisfy $(A_0x, y) = (x, A_0^*y)$ and $(A_1x, y) = \overline{(x, A_1^*y)}$ for all $x, y \in \mathcal{H}$, respectively. A real linear operator A is said to be *self-adjoint* if $A = A^*$. It is *unitary* if it is bijective and an isometry, i.e. $\|Ax\| = \|x\|$ for all $x \in \mathcal{H}$. A unitary operator is called *complex unitary* or *antiunitary* if it is complex linear or antilinear, respectively.

The spectral theory for real linear operators is not fully understood. It is known that the spectrum of a real linear operator is compact. It is possible for the spectrum to be empty. However, the spectrum of a self-adjoint real linear operator is known to be non-empty. It is not necessarily real but it is symmetric with respect to the real line. The spectrum of an antilinear operator is always circularly symmetric with respect to the origin. See [20] for more details.

Among the simplest antilinear operators are the so-called conjugations.

DEFINITION 2.1. An antilinear operator $\kappa \in \mathcal{B}(\mathcal{H})$ is a *conjugation* on \mathcal{H} if it is an involution, i.e. $\kappa^2 = I$.

PROPOSITION 2.2. For a conjugation κ on \mathcal{H} we have

$$\sigma_p(\kappa) = \sigma(\kappa) = \{e^{i\theta} : \theta \in \mathbb{R}\}.$$

Proof. The conjugation κ being antilinear, its spectrum is circularly symmetric with respect to the origin. For any nonzero $x \in \mathcal{H}$ we have

$$(\kappa - 1)(\kappa + 1)x = (\kappa^2 - 1)x = 0.$$

Now, either $(\kappa + 1)x = 0$, whence $(\kappa - 1)ix = 0$, or $(\kappa + 1)x \neq 0$, whence $(\kappa - 1)y = 0$ with $y = (\kappa + 1)x$. Thus $1 \in \sigma_p(\kappa)$.

On the other hand, if $r \neq 1$ is a non-negative real number, then

$$(\kappa + r)(\kappa - r)x_n = (1 - r^2)x_n$$

does not tend to zero for any sequence $\{x_n\}$ of unit vectors. That is, r is not in the approximate point spectrum $\sigma_a(\kappa)$. Similarly, $(\kappa^* - r)(\kappa^* + r)x = (1 - r^2)x \neq 0$ for any $x \neq 0$. Thus r is not in the compression spectrum $\sigma_c(\kappa)$. ■

Unitary conjugations, being norm-preserving, are of natural interest. Moreover, for antilinear (as well as for complex linear) operators, being involutory, self-adjoint or unitary are properties any two of which imply the third.

Given an orthonormal basis $\{e_n\}$ of \mathcal{H} , define κ , the *conjugation with respect to $\{e_n\}$* , to be the antilinear operator for which $\kappa e_n = e_n$ for all n . Clearly, κ is unitary. The content of the next proposition is the converse, i.e. for any unitary conjugation κ there is an orthonormal basis of \mathcal{H} with respect to which κ can be defined.

PROPOSITION 2.3. *Let κ be a unitary conjugation on \mathcal{H} . Then there is an orthonormal basis $\{e_n\}_{n=1}^\infty$ of \mathcal{H} such that $\kappa e_n = e_n$.*

Proof. By Proposition 2.2 there is a normalized eigenvector e_1 of κ such that $\kappa e_1 = e_1$. Now take a vector $y \in \{e_1\}^\perp$. Then also $\kappa y \in \{e_1\}^\perp$ since $(\kappa y, e_1) = (\kappa e_1, y) = (e_1, y) = 0$, i.e. $\text{span}\{e_1\}$ is a reducing subspace for κ . Let P_1 be the orthogonal projection onto $\text{span}\{e_1\}$. Then $P_1^\perp \kappa P_1^\perp$ is a conjugation on $P_1^\perp \mathcal{H}$ and has a unit eigenvector $e_2 \in \{e_1\}^\perp$. Continuing by induction, let P_n be the orthogonal projection onto $\text{span}\{e_1, \dots, e_n\}$ and take e_{n+1} to be the unit eigenvector of $P_n^\perp \kappa P_n^\perp$ in $(\text{span}\{e_1, \dots, e_n\})^\perp$. Then the set $\{e_n\}_{n=1}^\infty$ forms the required orthonormal basis of eigenvectors of κ . ■

Although unitary conjugations are simply defined and have nice properties, they are not necessarily simple to operate with, as illustrated by the following example.

EXAMPLE 2.4. Let S is the Beurling transform on $L^2(\mathbb{C})$ defined as a principal value integral

$$Sf(z) = -\frac{1}{\pi} \lim_{\varepsilon \rightarrow 0} \int_{|z-w|>\varepsilon} \frac{f(w)}{(z-w)^2} dw_1 dw_2, \quad w = w_1 + iw_2,$$

and τ the complex conjugation $f \mapsto \bar{f}$ on $L^2(\mathbb{C})$. Then the operator $S\tau$ is a unitary conjugation on $L^2(\mathbb{C})$. Namely, S is complex unitary and $S^{-1} = \tau S\tau$. Then $(S\tau)(S\tau) = I$ and $(S\tau)^* = \tau^* S^* = \tau\tau S\tau = S\tau$. For more details on the Beurling transform and its applications, see for example [2].

Classically, an orthogonal projection is an operator that is the identity on a closed subspace and zero on the orthogonal complement of this sub-

space. Analogously, we define an ‘antilinear orthogonal projection’ to be an antilinear counterpart of this notion.

DEFINITION 2.5. Let \mathcal{M} be a closed subspace of \mathcal{H} . An operator F on \mathcal{H} is said to be an *antilinear orthogonal projection* if its restriction to \mathcal{M} , $F|_{\mathcal{M}}$, is a unitary conjugation on \mathcal{M} , and F is zero on \mathcal{M}^\perp ⁽¹⁾.

Note that if P is the orthogonal projection onto \mathcal{M} and τ is some unitary conjugation on \mathcal{H} , then F is not in general given as $P\tau P$.

Orthogonal projections are in one-to-one correspondence with closed subspaces of \mathcal{H} . In strong contrast, there are a multitude of antilinear projections for any given closed subspace \mathcal{M} of \mathcal{H} .

EXAMPLE 2.6. Let $\{e_n\}$ be a set of orthonormal vectors spanning a closed subspace $\mathcal{M} \subset \mathcal{H}$. Then also the set $\{e^{i\theta_n}e_n\}$, $\theta_n \in \mathbb{R}$, is orthonormal and spans \mathcal{M} . The operators F_1 and F_2 defined by $F_1x = \sum_n (e_n, x)e_n$ and $F_2x = \sum_n (e^{i\theta_n}e_n, x)e^{i\theta_n}e_n$ for all $x \in \mathcal{H}$ are both antilinear projections onto \mathcal{M} . However, clearly $F_1 \neq F_2$.

The basis dependence of antilinear projections, or unitary conjugations when $\mathcal{M} = \mathcal{H}$, might seem unappealing operator-theoretically. However, it allows for defining a natural basis in the sense of Proposition 2.3. On the other hand, there are instances where antilinearity is the key to basis independence, as is illustrated by the following example.

EXAMPLE 2.7. In so-called bipartite quantum systems, a state $\sigma \in \mathcal{H} \otimes \mathcal{H}$ can be represented as

$$\sigma = \sum_n v_n \otimes e_n \quad \text{with} \quad \sum_n \|v_n\|^2 < \infty,$$

where $\{e_n\}$ is an orthonormal basis of \mathcal{H} . Defining L_σ as the unique antilinear (not complex linear) operator such that $L_\sigma e_n = v_n$ leads to the representation $\sigma = \sum_n L_\sigma e_n \otimes e_n$. However, this is independent of the choice of the orthonormal basis. See [1] for a detailed account. It is crucial that L_σ , the so-called relative state operator, be antilinear for this representation to be basis independent. This antilinear representation for states is advantageous when discussing quantum entanglement, for example in the study of Einstein–Podolsky–Rosen states [1] and of quantum teleportation [23].

Using the existence of a natural basis for a unitary conjugation in the sense of Proposition 2.3, we can show that any two unitary conjugations are related in a simple way.

PROPOSITION 2.8. *Let τ and κ be unitary conjugations on \mathcal{H} . Then there is a complex linear unitary operator U such that $\tau = U^*\kappa U$.*

⁽¹⁾ F is called a partial conjugation in [9].

Proof. Let $\{e_n\}$ (resp. $\{f_n\}$) be the orthonormal basis of \mathcal{H} for which $\tau e_n = e_n$ (resp. $\kappa f_n = f_n$) for all $n \geq 1$. Define U to be the complex linear operator such that $Ue_n = f_n$. Then U is unitary. Moreover $\kappa Ux = \kappa U \sum_n a_n e_n = \sum_n \overline{a_n} f_n$ and $U\tau x = U\tau \sum_n a_n e_n = \sum_n \overline{a_n} f_n$ for all $x \in \mathcal{H}$. Thus $\tau = U^* \kappa U$. ■

Clearly, if τ and κ are unitary conjugations, then $\kappa\tau$ is complex linear and unitary. Godič and Lucenko have proved that the converse holds, i.e., if U is a complex linear unitary operator, then there are two conjugations τ and κ such that $U = \tau\kappa$ [11].

3. Antilinear self-adjoint operator as a spectral integral. In this section we show how to represent an antilinear self-adjoint operator A on \mathcal{H} in the form

$$(3.1) \quad A = \int_{\sigma(A) \cap \mathbb{R}_+} \lambda dF(\lambda).$$

For comparison, recall that by using the spectral resolution, a complex linear self-adjoint operator H can be written as a spectral integral

$$H = \int_{\sigma(H)} \lambda dE(\lambda)$$

where E is a spectral measure on $\sigma(H)$. The spectral measure is defined on the σ -algebra of Borel subsets of $\sigma(H)$ and its values are orthogonal projections on \mathcal{H} . In addition, the spectral measure is required to be such that $E(\sigma(H)) = I$ and $E(\bigcup_n M_n) = \sum_n E(M_n)$ whenever $\{M_n\}$ is a disjoint sequence of sets. As an analogue, F in (3.1) is an antilinear spectral measure to be defined below.

To this end, let us start with the polar decomposition of A . Our exposition follows that of [16, p. 1346] where general antilinear operators on finite-dimensional spaces are considered. Recall that a self-adjoint complex linear operator B on \mathcal{H} is *positive* if $(Bx, x) \geq 0$ for all $x \in \mathcal{H}$.

PROPOSITION 3.1. *Every self-adjoint antilinear operator A on \mathcal{H} can be written in the polar form $A = |A|\tau = \tau|A|$, where τ is a unitary conjugation and $|A|$ is defined to be the complex linear positive square root of A^*A .*

Proof. Define $|A|$ to be the unique positive complex linear square root of the operator A^*A . For all $x \in \mathcal{H}$ we have $\| |A|x \| = \| Ax \|$. It follows that the null spaces of $|A|$ and A coincide, $\mathcal{N}(A) = \mathcal{N}(|A|)$. Since A and $|A|$ are self-adjoint, we have $\mathcal{H} = \mathcal{N}(A) \oplus \overline{\mathcal{R}(A)} = \mathcal{N}(|A|) \oplus \overline{\mathcal{R}(|A|)}$ and thus the closures of the ranges of A and $|A|$ also coincide. Denote $\mathcal{V}_1 = \overline{\mathcal{R}(|A|)} = \overline{\mathcal{R}(A)}$ and $\mathcal{V}_2 = \mathcal{N}(|A|) = \mathcal{N}(A)$. Then there is a unique antilinear isomorphism U_1 on \mathcal{V}_1 such that $A = U_1|A|$. Namely, for every $x \in \mathcal{V}_1 = \overline{\mathcal{R}(|A|)}$, there is $y \in \mathcal{H}$ such that $x = |A|y$. Define then $U_1x = Ay$. (Note that since $\mathcal{N}(|A|) = \mathcal{N}(A)$,

for the inverse images we have $A^{-1}(x) = |A|^{-1}(x)$, and the definition of U_1 does not depend on the choice of the preimage y .) Thus, U_1 is unitary.

Take then an arbitrary antilinear self-adjoint isomorphism U_2 on \mathcal{V}_2 . This can be done by choosing an orthonormal basis for \mathcal{V}_2 and defining U_2 to be the conjugation with respect to that basis. Finally, define τ on \mathcal{H} by $Ux = U_1x_1 + U_2x_2$, where $x_1 \in \mathcal{V}_1$ and $x_2 \in \mathcal{V}_2$.

Setting $H_2 = \tau|A|\tau^*$ we have the factorization $A = H_2\tau$. However, as A and H_2 are self-adjoint, $H_2^2 = H_2H_2^* = AA^* = A^*A$. Hence by the uniqueness of the square root, we have $H_2 = |A|$. Thus $A = \tau|A| = |A|\tau$.

Moreover, $A = \tau|A| = \tau^*|A|$ so that $\tau y = \tau^*y$ for all $y \in \mathcal{V}_1$. As U_2 was already chosen to be self-adjoint on \mathcal{V}_2 , the anti-unitary $\tau = U_1 \oplus U_2$ is also self-adjoint, thus a unitary conjugation. ■

Observe that in the proof above the self-adjointness of A was needed only in proving that τ is self-adjoint on \mathcal{V}_1 . Otherwise, the assumption $AA^* = A^*A$ would suffice. Note also that $|A|$ is unique and τ is non-unique only on $\mathcal{N}(A)$.

All the necessary information about the spectrum of a self-adjoint antilinear operator A is given by $|A|$. Indeed, $\sigma(|A|)$ lies on the non-negative real line \mathbb{R}_+ . We have $r \in \sigma(|A|)$ if and only if $r^2 \in \sigma(|A|^2) = \sigma(A^2)$, and the latter is equivalent to $r \in \sigma(A)$ by [20, Proposition 2.15]. In addition, it is known that the spectrum of an antilinear operator is circularly symmetric with respect to the origin. The fact that in this manner the spectra of A and $|A|$ are closely related leads to the following definition.

DEFINITION 3.2. Define the *antilinear spectral measure* F for an antilinear self-adjoint operator A on \mathcal{H} by

$$F(M) = E(M)\tau$$

for every Borel subset M of $\sigma(A) \cap \{\lambda \geq 0\} = \sigma(|A|)$. Here E is the spectral measure for $|A| = (A^*A)^{1/2}$ and τ is the unitary conjugation given by Proposition 3.1. For further convenience, denote by Σ the σ -algebra of Borel subsets of $\sigma(A) \cap \{\lambda \geq 0\} = \sigma(|A|)$.

For F to be appropriate for its role, it is crucial that $E(M)\tau = \tau E(M)$ for all $M \in \Sigma$. Even though τ is antilinear, standard textbook methods (as in [5, Theorem 10.2] or in [15, Theorem 40.2]) can be used to prove this. It should be observed, however, that the properties used in proving the following lemma require that the complex linear operator H be self-adjoint, not normal.

LEMMA 3.3. Let τ be antilinear and $H = \int \lambda dE(\lambda)$ be complex linear and self-adjoint where E is the spectral measure for H . If $\tau H = H\tau$, then $E(M)\tau = \tau E(M)$ for all $M \in \Sigma$.

Proof. We have $p(H)\tau = \tau p(H)$ for every real polynomial p . Then for all $x, y \in \mathcal{H}$,

$$(3.2) \quad \int p(\lambda) d(E(\lambda)x, \tau^*y) = (p(A)x, \tau^*y) = \overline{(p(A)\tau x, y)} \\ = \overline{\int p(\lambda) d(E(\lambda)\tau x, y)},$$

from which we infer that

$$(3.3) \quad (\tau E(M)x, y) = \overline{(E(M)x, \tau^*y)} = (E(M)\tau x, y).$$

Thus $E(M)$ and τ commute. ■

From this it follows that an antilinear self-adjoint operator may be represented in the form (3.1). Analogously to classical spectral measures, the antilinear spectral measure satisfies the following:

(i) The values of F are antilinear projections, i.e.

$$F(M)^2 = E(M) \quad \text{and} \quad F(M)^* = (E(M)\tau)^* = E(M)\tau = F(M).$$

(ii) $F(\sigma(A)) = \tau$.

(iii) $F(\bigcup_n M_n) = \sum_n F(M_n)$ for any disjoint sequence $\{M_n\}$ of sets.

4. Weyl–von Neumann theorem for antilinear self-adjoint operators. In this section we aim to prove an analogue of the Weyl–von Neumann theorem. Naturally, the question arises why the polar decomposition of Proposition 3.1 with the classical Weyl–von Neumann theorem does not provide the desired result directly. We may certainly write $A = |A|\tau$ and use the representation $|A| = D + K$ of the Weyl–von Neumann theorem. This provides us with a compact operator K and an operator D diagonal with respect to an orthonormal basis $\{e_n\}$ of \mathcal{H} . Then clearly $A = D\tau + K\tau$ where $K\tau$ is compact. However, we cannot claim that $D\tau$ is diagonal. This would be the case only if the orthonormal basis diagonalizing τ were the same as the one diagonalizing D .

4.1. The main theorem. Recall the notion of diagonalizability. It is in effect unitary diagonalizability, and as such more stringent than other, more general definitions of diagonalizability for Hilbert space operators (cf. [17]).

DEFINITION 4.1. An operator A on \mathcal{H} is *diagonalizable* if there exists an orthonormal basis $\{e_n\}$ of \mathcal{H} such that $Ae_n = a_n e_n$ for all n for some complex numbers a_n , i.e. if there is an orthonormal set of eigenvectors spanning \mathcal{H} . Then A is said to be *diagonal with respect to* $\{e_n\}$.

Let us glance at the finite-dimensional diagonalizability first. It is interesting in its own right due to its frequent occurrence in applications. In addition, the proof of the main theorem relies on it.

PROPOSITION 4.2. *Let \mathcal{H} be a finite-dimensional Hilbert space and let $A \in \mathcal{B}(\mathcal{H})$ be an antilinear self-adjoint operator on \mathcal{H} . Then A is unitarily diagonalizable.*

Proof. We can factor $A = A_{\#}\tau$ where τ is represented by complex conjugation on \mathbb{C}^n . Then $(A_{\#}\tau)^* = \tau^*A_{\#}^* = A_{\#}^T\tau$, that is, $A_{\#}$ is complex symmetric. By the Takagi factorization (cf. e.g. [18]) there is a unitary matrix U such that $UA_{\#}U^T = D$ where D is diagonal. Thus $D\tau = UAU^T\tau = UDU^*$, i.e. A is diagonalizable since $D\tau$ is diagonal with respect to the standard basis. ■

Diagonalizability in the antilinear case is not a trivial matter, though. Recall that almost all complex matrices are diagonalizable in the sense that the probability is one for a randomly picked complex linear operator on a finite-dimensional Hilbert space to be diagonalizable. However, diagonalizable antilinear operators are a lot more scarce. The probability of a randomly picked antilinear operator on an n -dimensional Hilbert space to be diagonalizable is $2^{-n(n-1)/2}$ (see [19] for details).

Analogously to the complex linear case, we define singular values and Schatten p -class operators as follows.

DEFINITION 4.3. Define the *singular values* $s_n(A)$, $n = 1, 2, \dots$, of a compact antilinear operator A as the eigenvalues of the complex linear positive operator $|A| = (A^*A)^{1/2}$ in non-increasing order of magnitude. We say that A is in the *Schatten p -class* $\mathcal{B}_p(\mathcal{H})$, $1 \leq p < \infty$, if

$$\|A\|_p = \left(\sum_n s_n(A)^p \right)^{1/p} < \infty.$$

Note that if we factor a compact antilinear operator A as $A = A_{\#}\tau$ with τ a unitary conjugation and $A_{\#} = A\tau$, then $s_n(A) = s_n(A_{\#})$. This follows from the fact $\sigma(|A_{\#}|) = \sigma(|A|)$, which holds since $|A_{\#}| = (\tau^*A^*A\tau)^{1/2}$ and $\sigma(|A_{\#}|)$ is real.

From this connection between A and $A_{\#}$, the following is immediate. The *rank* of an antilinear operator is defined to be the dimension of its range.

LEMMA 4.4. *For an antilinear operator A of rank at most n , we have $\|A\|_p \leq n^{1/p}\|A\|$.*

Now we can state the analogue of the Weyl-von Neumann theorem.

THEOREM 4.5. *Let A be a self-adjoint antilinear operator on \mathcal{H} , $\varepsilon > 0$ and $1 < p < \infty$. Then there is a diagonalizable self-adjoint antilinear operator D such that $A - D$ is compact and $\|A - D\|_p < \varepsilon$.*

The steps in proving that A is the sum of a diagonalizable operator D and a Schatten p -class operator follow those taken in [5, pp. 212–213]; see also [21, Chapter X], and [22] for extension from $p = 2$ to $1 < p < \infty$.

However, a modification is needed: in the following proposition we have to require that $f = \tau f \in \mathcal{H}$.

LEMMA 4.6. *Let $A = |A|\tau$ be a self-adjoint antilinear operator and $\tau f = f \in \mathcal{H}$. Then for any $\varepsilon > 0$ there is a finite rank projection P and a self-adjoint antilinear operator $K \in \mathcal{B}_p(\mathcal{H})$, $1 < p < \infty$, such that $f \in P\mathcal{H}$, $\|K\|_p < \varepsilon$, and $A + K$ is reduced by P . In addition, $P\tau = \tau P$.*

Proof. Factor A in the form $A = \tau|A| = |A|\tau$ as in Lemma 3.1. The self-adjoint operator $|A|$ has a spectral decomposition $|A| = \int \lambda dE(\lambda)$ with respect to the spectral measure E . Assume $\sigma(|A|) \subset [a, b]$, where $[a, b]$ is an interval of the non-negative real line. Partition $[a, b]$ into n equal subintervals M_1, \dots, M_n of length $(b - a)/n$ each and let λ_k be the midpoint of the interval M_k . Set $f_k = E(M_k)\tau f = E(M_k)f$, and define $g_k = f_k/\|f_k\|$ if $f_k \neq 0$, and $g_k = 0$ otherwise. Denote for convenience $c_k = 1/\|f_k\|$. Thus we have $g_k \in E(M_k)\tau\mathcal{H}$, whence $g_j \perp g_k$ for $j \neq k$. Then

$$\|(A - \lambda)g_k\| = \||A|\tau c_k E(M_k)f - \lambda c_k E(M_k)f\| = \||A| - \lambda\|g_k\| \leq \frac{b - a}{n}.$$

Denoting by P the orthogonal projection onto $\text{span}\{g_k\}_{k=1}^n = \text{span}\{f_k\}_{k=1}^n$, we get

$$(4.1) \quad \|P^\perp Ag_k\| = \|P^\perp(A - \lambda)g_k\| \leq \frac{b - a}{n}.$$

We have $Ag_k \in AE(M_k)\mathcal{H} = E(M_k)A\mathcal{H} \subset E(M_k)\mathcal{H}$, so that $Ag_k \perp g_j$ for $k \neq j$. Hence

$$P^\perp Ag_k = Ag_k - \sum_j (Ag_k, g_j)g_j = Ag_k - (Ag_k, g_k)g_k \in E(M_k)\mathcal{H}$$

so that also $P^\perp Ag_k \perp P^\perp Ag_j$ for $k \neq j$. Using this orthogonality, we obtain

$$\begin{aligned} \|P^\perp APh\|^2 &= \left\| \sum_k (g_k, h)P^\perp Ag_k \right\|^2 = \sum_k |(g_k, h)|^2 \|P^\perp Ag_k\|^2 \\ &\leq \|h\|^2 \left(\frac{b - a}{n} \right)^2 \end{aligned}$$

for all $h \in \mathcal{H}$. Thus $\|P^\perp AP\| \leq (b - a)/n$ with $P^\perp AP$ having rank at most n . By Lemma 4.4, $\|P^\perp AP\|_p \leq (b - a)n^{-1/q}$ with $1/p + 1/q = 1$.

Define $B = PAP + P^\perp AP^\perp$ and $K = -P^\perp AP - PAP^\perp$. Then B and K are self-adjoint antilinear operators and $A = B - K$. The operator B is reduced by P , K has finite rank, and $\|K\|_p \leq 2(b - a)/n^{1/q}$, which can be made arbitrarily small by a suitable choice of n .

Finally,

$$\begin{aligned} \tau Px &= \tau \sum_k (x, c_k E(M_k) f) c_k E(M_k) f = \sum_k (c_k E(M_k) f, x) c_k E(M_k) \tau f \\ &= \sum_k (\tau x, \tau c_k E(M_k) f) c_k E(M_k) f = P \tau x \end{aligned}$$

for all $x \in \mathcal{H}$, so that $P \tau = \tau P$. ■

Using the previous lemma, one can prove the Weyl-von Neumann theorem for antilinear self-adjoint operators.

Proof of Theorem 4.5. Let $\{e_n\}$ be an orthonormal basis of \mathcal{H} such that $\tau e_n = e_n$ for all n . Apply Lemma 4.6 with $f = e_1$ to get a finite rank projection P_1 and a self-adjoint operator $K_1 \in \mathcal{B}_p(\mathcal{H})$ with $\|K_1\|_p < \varepsilon/2$ such that $A + K_1$ is reduced by P_1 and $e_1 \in P_1 \mathcal{H}$. Apply the lemma again to $(A + K_1)|_{(P_1 \mathcal{H})^\perp}$ with the vector $f = P_1^\perp e_2 = \tau f$ to get a self-adjoint operator $K_2 \in \mathcal{B}(P_1^\perp \mathcal{H})$ and a projection P_2 such that $P_1^\perp e_2 \in P_2 \mathcal{H}$, $\|K_2\|_p < \varepsilon/2^2$ and $A + K_1 + K_2$ is reduced by P_2 . Extend K_2 to all of \mathcal{H} by setting $K_2 y = 0$ for all $y \in P_1 \mathcal{H}$. Note that $e_1, e_2 \in (P_1 + P_2) \mathcal{H}$.

By induction we get a sequence $\{P_n\}$ of finite rank projections and a sequence $\{K_n\}$ of self-adjoint operators such that

- (i) $\|K_n\|_p < \varepsilon/2^n$,
- (ii) $P_j P_k = 0$ for $j \neq k$,
- (iii) $e_n \in (\sum_{k=1}^n P_k) \mathcal{H}$,
- (iv) $A + K_1 + \dots + K_n$ is reduced by $P_1 + \dots + P_n$,
- (v) $K_n (P_1 + \dots + P_{n-1}) = 0$.

Set $K = \sum_n K_n$, $D = A + K$ and $D_n = D|_{P_n \mathcal{H}}$. Then $\|K\|_p < \varepsilon$ by property (i) and D is self-adjoint. Properties (ii) and (iii) imply that $\sum_n P_n = I$. Properties (iv) and (v) imply that D is reduced by $P_n \mathcal{H}$ for all n and $D = \bigoplus_n D_n$.

Since each of the spaces $P_n \mathcal{H}$ is finite-dimensional, by Proposition 4.2 there is an orthonormal basis of $P_n \mathcal{H}$ that diagonalizes D_n . Thus D is a diagonalizable operator. ■

Note that a diagonalizable antilinear operator can be assumed to have a non-negative diagonal. Namely, assume D on \mathcal{H} is diagonal with respect to the orthonormal basis $\{e_n\}$, i.e. $D e_n = d_n e_n = |d_n| e^{i\theta_n} e_n$. Then for all $x = \sum_n (x, e_n) e_n \in \mathcal{H}$,

$$Dx = \sum_n (e_n, x) d_n e_n = \sum_n (e^{i\theta_n/2} e_n, x) |d_n| e^{i\theta_n/2} e_n,$$

so that D is diagonal with respect to the orthonormal basis $\{e^{i\theta_n/2} e_n\}$ with non-negative diagonal.

4.2. Finite rank generalization to real linear operators. The question whether there is a more general version of Theorem 4.5 is treated in finite dimensions.

LEMMA 4.7. *Let N be a complex linear normal operator and S an antilinear self-adjoint operator on a finite-dimensional Hilbert space \mathcal{H} such that $NS = SN^*$. Then N , N^* and S have a common eigenvector.*

Proof. Let $y \in \mathcal{W} = \{x \in \mathcal{H} : Nx = \lambda x\} = \{x \in \mathcal{H} : N^*x = \bar{\lambda}x\}$ for some eigenvalue $\lambda \in \mathbb{C}$ of N . Then $NSy = SN^*y = S\bar{\lambda}y = \lambda Sy$. Thus $Sy \in \mathcal{W}$. Therefore, the subspace \mathcal{W} is S -invariant.

The restriction $S|_{\mathcal{W}}$ is an antilinear self-adjoint operator on \mathcal{W} , and as such [20] has an eigenvalue $r \in \mathbb{R}$ corresponding to an eigenvector $z \in \mathcal{W}$. Then z is the desired common eigenvector. ■

PROPOSITION 4.8. *Let $A = N + S$ be a real linear operator on a finite-dimensional Hilbert space \mathcal{H} , where N is complex linear normal, S is antilinear self-adjoint and they satisfy $NS = SN^*$. Then A is unitarily diagonalizable.*

Proof. By Lemma 4.7 there exists a unit vector $e_1 \in \mathcal{H}$ such that $Ne_1 = \lambda e_1$, $N^*e_1 = \bar{\lambda}e_1$ and $Se_1 = re_1$ for some $\lambda \in \mathbb{C}$ and $r \in \mathbb{R}$. Split $\mathcal{H} = \text{span}\{e_1\} \oplus \text{span}\{e_1\}^\perp$. Then obviously $Ax \in \text{span}\{e_1\}$ for $x \in \text{span}\{e_1\}$. But we also have

$$(e_1, Ay) = (e_1, Ny) + (e_1, Sy) = (N^*e_1, y) + (Se_1, y) = \lambda(e_1, y) + r(e_1, y) = 0$$

for every $y \in \text{span}\{e_1\}^\perp$. Thus $Ay \in \text{span}\{e_1\}^\perp$. Hence, $A = D_1 \oplus A_1$, where D_1 is trivially diagonal on $\text{span}\{e_1\}$ and A_1 is a real linear operator on $\text{span}\{e_1\}^\perp$ satisfying the assumptions of the proposition. Iterate the procedure to finally get an orthonormal basis $\{e_n\}$ of \mathcal{H} . ■

This raises the question whether, similarly to the proof of Theorem 4.5, a reduction to the finite-dimensional case can be made to prove an analogue of the Weyl–von Neumann theorem for real linear operators satisfying the commutation property above. However, at this point, it remains unclear whether this can be done.

4.3. Complex symmetric operators. In what follows, we make some remarks on complex symmetric operators and their relation to antilinear self-adjoint operators. A complex linear operator S on \mathcal{H} is called τ -symmetric if

$$\tau S^* \tau = S,$$

where τ is a unitary conjugation. It is called *complex symmetric* if it is τ -symmetric with respect to some unitary conjugation τ . Complex symmetric operators have been the object of recent investigations, and they have

been shown to include a variety of important operators, for example all normal operators, Hankel operators, compressed Toeplitz operators and many standard integral operators [8, 9, 10].

Complex symmetric operators and antilinear operators are related in the following manner.

PROPOSITION 4.9. *If the complex linear operator S is τ -symmetric on \mathcal{H} , then the operator $S\tau$ is antilinear self-adjoint. Conversely, if the operator A on \mathcal{H} is antilinear self-adjoint, then $A\tau$ is τ -symmetric for any unitary conjugation τ .*

Proof. The first assertion follows from

$$(S\tau)^* = \tau^* S^* = \tau S^* \tau^2 = S\tau.$$

The second follows from $(A\tau)^* = \tau^* A^* = \tau(A\tau)\tau$. ■

This connection may be useful in some contexts, as defining antilinear self-adjointness is basis independent whereas complex symmetry is defined essentially through the choice of an orthonormal basis by fixing a unitary conjugation.

In finite dimensions, by the Takagi factorization, a matrix S is complex symmetric, $S = S^T$, if and only if it is *unitarily conidiagonalizable*, i.e. there exists a unitary matrix U and a diagonal matrix D (with non-negative entries) such that $S = UDU^T$. Using Theorem 4.5 and the correspondence with antilinear operators, it can be seen that, in the infinite-dimensional case, complex symmetric operators are arbitrarily close to conidiagonalizable operators. Here, the analogue of the transpose of U in the infinite-dimensional setting is $\tau U^* \tau$.

PROPOSITION 4.10. *Let S be a complex symmetric operator on \mathcal{H} with respect to the unitary conjugation τ . Then for any $\varepsilon > 0$ there exists a complex linear unitary operator U and a diagonalizable complex linear operator D such that*

$$\|S - UD\tau U^* \tau\| < \varepsilon.$$

Proof. Let $\{e_n\}$ be the orthonormal basis of \mathcal{H} for which $\tau e_n = e_n$. Since $S\tau$ is antilinear and self-adjoint, by Theorem 4.5 there is an antilinear diagonalizable operator \tilde{D} such that $\|S\tau - \tilde{D}\| \leq \|S\tau - \tilde{D}\|_p < \varepsilon$. Let $\{f_n\}$ be the orthonormal basis diagonalizing \tilde{D} , i.e. $\tilde{D}f_n = d_n f_n$ where $d_n \geq 0$. Define U by $Ue_n = f_n$. Then for all $x \in \mathcal{H}$ we have

$$\begin{aligned} S\tau x - Dx &= S\tau x - \sum_n d_n (f_n, x) f_n = S\tau x - \sum_n d_n (Ue_n, x) Ue_n \\ &= S\tau x - U \sum_n d_n (e_n, U^* x) e_n = (S - UD\tau U^* \tau)\tau x, \end{aligned}$$

where D is a complex linear operator, diagonal with respect to $\{e_n\}$. From this we infer, upon using the norm estimate given by Theorem 4.5, that $\|S - UD\tau U^*\tau\| < \varepsilon$. ■

We also have the following.

PROPOSITION 4.11. *Let S be a complex symmetric operator on \mathcal{H} with respect to the unitary conjugation τ . Then there exist a unitary conjugation κ and a diagonalizable complex linear operator D with non-negative diagonal such that κ and D are diagonalized with respect to the same orthonormal basis and*

$$\|S - \tau D \kappa\|_p < \varepsilon.$$

Proof. Since τS is antilinear self-adjoint, by Theorem 4.5 there exists an antilinear operator \tilde{D} , diagonal with respect to an orthonormal basis $\{e_n\}$, with a non-negative diagonal, such that $\|\tau S - \tilde{D}\|_p < \varepsilon$. We can factor $\tilde{D} = D\kappa$ where D is complex linear diagonal with respect to $\{e_n\}$ and κ is the unitary conjugation with respect to $\{e_n\}$. Then $\|S - \tau D \kappa\|_p < \varepsilon$. ■

Acknowledgements. The author is grateful to the anonymous referee and Prof. Marko Huhtanen for their valuable comments on the manuscript.

References

- [1] R. Arens and V. S. Varadarajan, *On the concept of Einstein–Podolsky–Rosen states and their structure*, J. Math. Phys. 14 (2000), 638–651.
- [2] K. Astala, T. Iwaniec and G. Martin, *Elliptic Partial Differential Equations and Quasiconformal Mappings in the Plane*, Princeton Math. Ser. 48, Princeton Univ. Press, Princeton, NJ, 2009.
- [3] K. Astala and L. Päiväranta, *Calderón’s inverse conductivity problem in the plane*, Ann. of Math. (2) 163 (2006), 265–299.
- [4] I. D. Berg, *An extension of the Weyl–von Neumann theorem to normal operators*, Trans. Amer. Math. Soc. 160 (1971), 365–371.
- [5] J. B. Conway, *A Course in Operator Theory*, Grad. Stud. Math. 21, Amer. Math. Soc., Providence, RI, 2000.
- [6] V. D. Didenko and B. Silbermann, *Approximation of Additive Convolution-like Operators: Real C^* -Algebra Approach*, Frontiers Math., Birkhäuser, Basel, 2008.
- [7] L. Elsner and K. D. Ikramov, *Normal matrices: an update*, Linear Algebra Appl. 285 (1998), 291–303.
- [8] S. R. Garcia and M. Putinar, *Complex symmetric operators and applications*, Trans. Amer. Math. Soc. 358 (2006), 1285–1315.
- [9] S. R. Garcia and M. Putinar, *Complex symmetric operators and applications. II*, Trans. Amer. Math. Soc. 359 (2007), 3913–3931.
- [10] S. R. Garcia and W. R. Wogen, *Some new classes of complex symmetric operators*, Trans. Amer. Math. Soc. 362 (2010), 6065–6077.
- [11] V. Ī. Godič and I. E. Lucenko, *On the representation of a unitary operator in the form of a product of two involutions*, Uspekhi Mat. Nauk 20 (1965), no. 6, 64–65 (in Russian).

- [12] R. Grone, C. R. Johnson, E. M. Sa and H. Wolkowicz, *Normal matrices*, Linear Algebra Appl. 87 (1987), 213–225.
- [13] P. R. Halmos, *Ten problems in Hilbert space*, Bull. Amer. Math. Soc. 76 (1970), 887–933.
- [14] P. R. Halmos, *Continuous functions of Hermitian operators*, Proc. Amer. Math. Soc. 31 (1972), 130–132.
- [15] P. R. Halmos, *Introduction to Hilbert Space and the Theory of Spectral Multiplicity*, Chelsea Publ., New York, NY, 1951.
- [16] F. Herbut and M. Vujčić, *Basic algebra of antilinear operators and some applications I*, J. Math. Phys. 8 (1967), 1345–1354.
- [17] D. A. Herrero, *Triangular operators*, Bull. London Math. Soc. 23 (1991), 513–554.
- [18] R. A. Horn and C. R. Johnson, *Matrix Analysis*, corrected reprint of the 1985 original, Cambridge Univ. Press, Cambridge, 1990.
- [19] M. Huhtanen and A. Perämäki, *Orthogonal polynomials for the \mathbb{R} -linear generalized minimal residual method*, J. Approx. Theory 167 (2013), 220–239.
- [20] M. Huhtanen and S. Ruotsalainen, *Real linear operator theory and its applications*, Integral Equations Operator Theory 69 (2011), 113–132.
- [21] T. Kato, *Perturbation Theory for Linear Operators*, Classics Math., reprint of the 1980 edition, Springer, Berlin, 1995.
- [22] S. T. Kuroda, *On a theorem of Weyl–von Neumann*, Proc. Japan Acad. 34 (1958), 11–15.
- [23] Z. Kurucz, M. Koniorczyk, P. Adam and J. Janszky, *An operator description of entanglement matching in quantum teleportation*, J. Optics B: Quantum and Semi-classical Optics 5 (2003), S627–S632.
- [24] J. von Neumann, *Charakterisierung des Spektrums eines Integraloperators*, Actualités Sci. Indust. 229, Hermann, Paris, 1935.
- [25] M. Putinar and H. S. Shapiro, *The Friedrichs operator of a planar domain*, in: Complex Analysis, Operators, and Related Topics, Oper. Theory Adv. Appl. 113, Birkhäuser, Basel, 2000, 303–330.
- [26] D. Voiculescu, *A non-commutative Weyl–von Neumann theorem*, Rev. Roumaine Math. Pures Appl. 21 (1976), 97–113.
- [27] H. Weyl, *Über beschränkte quadratische Formen, deren Differenz vollstetig ist*, Rend. Circ. Mat. Palermo 27 (1909), 373–392.

Santtu Ruotsalainen
Institute of Mathematics
Aalto University
P.O. Box 11100
FI-00076 Aalto, Finland
E-mail: Santtu.Ruotsalainen@aalto.fi

Received March 21, 2012

(7462)

